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Ultrafast response of tunnel injected quantum dot based semiconductor optical amplifiers in the 1300 nm range

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The ultrafast gain and refractive index dynamics of tunnel injected quantum dot based semiconductor optical amplifiers in the 1300 nm range are investigated using a heterodyne pump probe technique. In the gain regime, ground state wavelengths exhibit full gain recovery in less than 10 ps up to 3 times transparency, attributed to enhanced carrier refilling via the injector layer. The effect of the injector can also been seen in unusual phase dynamics at excited state wavelengths at this injection level. © *2012 American Institute of Physics*. [doi:10.1063/1.3686901]

Quantum dot (QD) based optical materials and devices have been studied intensively due to a desire for atom-like optical properties in a compact solid state structure.[1] Application areas where QD based structures have outperformed their bulk and quantum well counterparts include monolithic passive[2] and active[3] mode locked lasers (MMLs), electrooptic modulators,[4] and saturable absorber mirrors.[5] Characteristics such as reduced sensitivity to optical feedback and reduced alpha-parameter have made such materials attractive as laser sources.[6] However, at the technologically important 1.3 μm wavelength, good modulation performance has been difficult to realise due to the significant amount of "hot carriers" present in the system.[7] Tunnel injection (TI) structures were proposed to overcome this limitation[8] and have demonstrated modulation bandwidths in excess of 11 GHz in the 1.3 μm range[9] under quasi-cw conditions. TI based devices have also been investigated in the 1060 nm range for high power applications,[10] in spin polarised lasers,[11] and with quantum dash structures for operation in the 1550 nm range.[12]

Recently, dilute nitride based injector levels have been investigated as an alternative to InGaAs layers to overcome issues of excessive strain and tunability, and efficient electron tunnelling was realised.[7,13] However, improved modulation performance has not yet been demonstrated. In order to address this point, we present an experimental analysis of the ultrafast gain and refractive index dynamics in a semiconductor optical amplifier structure. Measurements of the ground state (GS) gain dynamics reveal full recovery within 10 ps of a strong depleting pulse. The corresponding refractive index dynamics contains an additional long time component connected to non-resonant carrier relaxation in adjacent layers. In addition, excited state (ES) measurements indicate anomalous phase dynamics due to the presence of the TI layer.

The SOA active region consisted of 5 repetitions of 15 nm GaAs, 10 nm carbon p-doped GaAs (1.5×10^{17} cm^{-3}, 10 nm GaAs, a self assembled layer of QDs, 3 nm GaAs barrier and a 10 nm $GaIn_{0.15}AsN_{0.04}$ injector layer. The carbon doping was performed to enhance the modulation characteristics as outlined in Ref. 14. Control samples were also fabricated without the injector layer. The SOAs had angled, antireflection coated facets and were tested in a standard single wavelength heterodyne pump probe setup.[15] The QD's GS or first ES could be selectively investigated by changing the wavelength of the pump-probe system.

Room temperature amplified spontaneous emissions (ASE) of the SOA together with photo-luminescence (PL) spectra of the material are shown in Figure 1 and indicate GS emission around 1270 nm with the onset of ES emission visible around 1200 nm. It is important to note that similar PL measurements on a control sample without the TI layer yielded much higher PL intensities, indicating that the inclusion of the dilute nitride injector layer results in a large increase in defect assisted nonradiative recombination. As shown in the PL zoom in Figure 1, a much weaker additional peak is visible around 1060 nm which is also not present in the control sample and is attributed to the injector level.

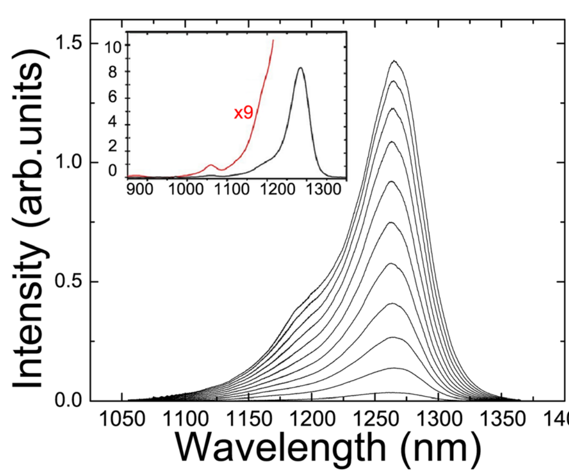

FIG. 1. (Color online) Room temperature amplified spontaneous emission of TI SOA up to 210 mA (3 times transparency). Inset: Photo-luminescence spectra including an amplitude zoom to illustrate the presence of the injector layer at 1060 nm.

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The pump induced gain dynamics, together with multi-exponential fits and characteristic times are shown in Figure 2. The GS gain dynamics (panel (a)) displays 2 main features: (1) Below GS transparency (10 mA case), where the pump pulse injects carriers to the sample, we have a relatively fast absorption recovery. In this situation, the absorption drops to 20% of its peak value within 20 ps, in contrast to the control sample or the literature where the longer timescale usually dominates.[16] This corresponds to a decrease in the total recombination time and is attributed to the increased non-radiative recombination due to the dilute nitride layer. (2) Above GS transparency, when the pump pulse removes carriers from GS, we have very fast recovery dynamics. The gain returns to its unperturbed level in less than 10 ps, up to ∼3 times transparency (current limited by driver). Multi-exponential timescales of 0.4 ps and 1.5 ps are extracted from the time traces, the shorter of these is close to the pulsewidth of the system and can be associated with non-linear effects such as two photon absorption (TPA) and four wave mixing (FWM). Thus, the longer time (1.5 ps) represents the limiting recovery timescale in the system for the 150 mA and 200 mA cases. Similar measurements from the control sample and the literature (e.g., see Ref. 16) show a much slower recovery, and so we attribute the fast recovery of the GS population to enhance supply of carriers from the injector level.

The corresponding ES gain dynamics is shown in panel (b) where exponential fitting results in only 2 timescales. The ES remains below transparency over the current range used and so carriers are always added to the ES by the pump pulse. At the lowest current where the GS is also absorbing, the ES fast timescale is somewhat shorter than the two shortest times in the GS absorption case. Factors which may be responsible for this decrease include the increased proximity of the injector layer and associated nonradiative recombination, as well as fast carrier relaxation from the ES to available GS levels. As the ES states are always below transparency over the current range used, it is not possible to compare to the higher injection GS recoveries where carriers are removed from system by the pump pulse.

The pump induced phase dynamics with multiexponential fits and characteristic times are shown in Figure 3. The phase dynamics at GS is shown in panel (a) and shows timescales in the same range above and below GS transparency together with a large component which recovers over a much longer timescale, particularly above transparency. This type of offset is also seen in the control sample and is associated with a phase contribution from adjacent layers that recovers

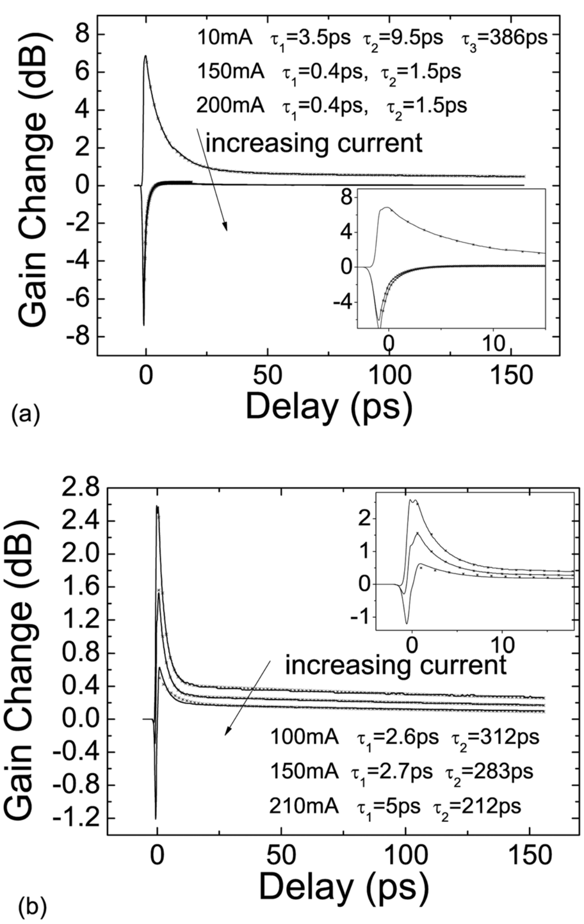

FIG. 2. Gain dynamics at GS (a) and ES (b) wavelengths with corresponding multiexponential fits and timescales. A zoom of the dynamics over the first 15 ps is shown in inset. GS injection levels were 10 mA, 80 mA, 150 mA, and 200 mA with transparency at ∼70 mA (150, 200 mA overlapping). ES injection levels were 100 mA, 150 mA, and 210 mA.

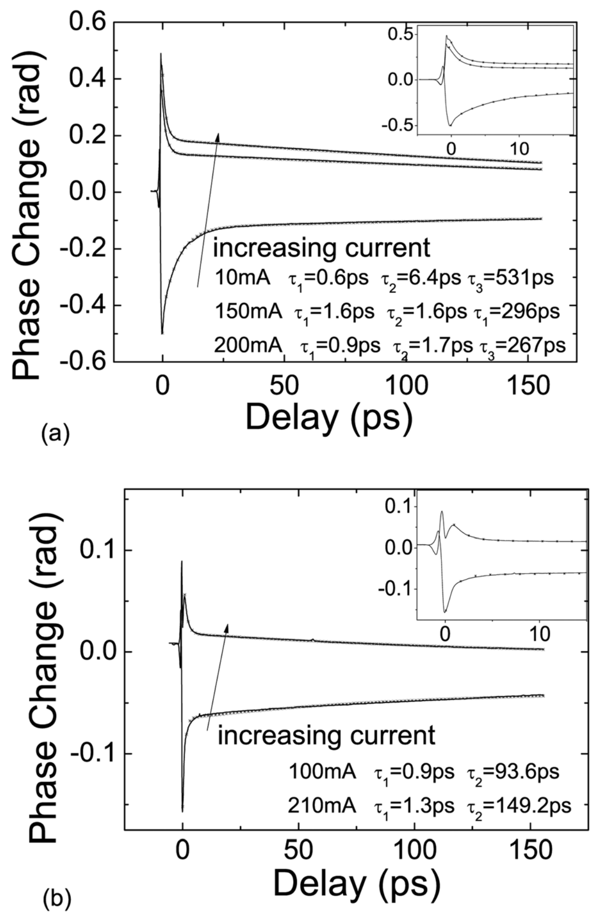

FIG. 3. Phase dynamics at GS (a) and ES (b) wavelengths with corresponding multiexponential fits and timescales. A zoom of the dynamics over the first 15 ps is shown in inset. GS injection levels were 10 mA, 80 mA, 150 mA, and 200 mA with transparency at ∼70 mA. ES injection levels were 100 mA, 150 mA, and 210 mA.

on a timescale related to the radiative lifetime of those layers (up to 1 ns depending on the layer).[17] The phase dynamics of the ES is shown in panel (b) and exhibits a similar behaviour to that seen for the GS absorbing regime, albeit with a faster initial recovery linked to the faster ES gain recovery at this injection level. However, at increased injections, a sign change occurs in the phase even though the ES is still absorbing. Similar behaviour is not seen in the control (or reported in the literature) and so we attribute this change in sign to the presence of carriers in the injector layer.

In the case where both gain and phase dynamical information are available, it is usual to consider the effective or dynamical α-factors (here termed $\alpha_d(t)$) in order to gain additional understanding of the QD SOA and its possible applications.[18,19] It can be calculated using the relation

$$\alpha_d(t) = -\frac{4\pi}{\lambda}\frac{\Delta n(t)}{\Delta g(t)},$$

where $\Delta n(t), \Delta g(t)$ are the pump induced refractive index and gain transients as a function of time. An alternative definition based on the derivatives of the refractive index and gain responses could also be used (see, e.g., Ref. 19) and lead to very similar results.

The results of such a calculation are shown in Figure 4 for the absorbing regimes of the GS and ES. In the GS gain regime, the fast recovery of the gain (less than 10 ps) results in a full decoupling of the gain and phase dynamics and a strongly varying "giant" alpha factor due to the negligible gain change beyond 10 ps (In Ref. 20, a "giant" steady state alpha results when GS gain and phase are decoupled due to GS gain saturation). In the GS absorption regime, $\alpha_d(t)$ reaches a maximum value of $\sim$1.7 after which it reduces slowly. In the ES absorption regime at 100 mA, $\alpha_d(t)$ reaches a value of $\sim$1.4 within 20 ps after which it is constant, indicating that the gain and refractive index dynamics are both linked to a similar recombination time. However, this situation changes as the current increases to 210 mA. Here, $\alpha_d(t)$ becomes negative, reaching a minimum value of ~ -0.75 after 20 ps and increasing slowly thereafter. This behaviour indicates that the gain and phase are linked to different carrier populations (mainly the ES and TI states, respectively) which recover at different rates.

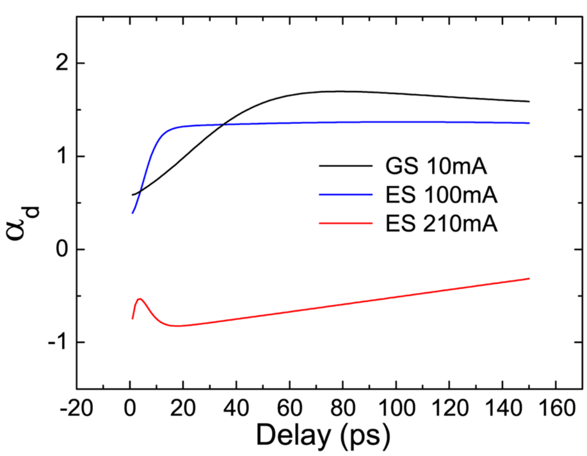

FIG. 4. (Color online) Dynamical alpha factor for GS and ES absorption regimes. Note the change in sign for the high injection (210 mA) ES case.

To summarise, we have carried out heterodyne pump probe measurements of the gain and phase dynamics of a QD based structure incorporating a dilute nitride TI layer. Notwithstanding the increased nonradiative recombination due to the dilute nitride layer, we identified a high speed (<10 ps) gain recovery in the 1300 nm range due to the incorporation of the TI layer which may be important for future high speed laser applications. In order to translate this high speed gain recovery into high speed laser devices, the differential gain needs to be increased by improving the quality of the nitride layer and thereby reducing the level of nonradiative recombination. In addition, the inclusion of a TI layer results in unusual phase dynamics in the ES wavelength range and a negative alpha factor which may be important for other laser applications of this material system. In order to evaluate directly the efficiency of the tunnelling process, selective injection into tunnelling or barrier layers followed by measurement of the subsequent response of the ES is required. However, in quantum cascade structures, anomalous current voltage characteristics can also provide an indication of variation of tunnelling conditions.[21] In our case, no such features were present at room temperature, representing an early indication of constant tunnelling conditions over the operation range examined.

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